MODELING OF IGNITION OF COMBUSTION OF DUST\AIR MIXTURE IN AN ENCLOSED VOLUME.

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Abstract

The ignition of combustion in a carbon dust\gas mixture was studied, taking into account radiative, conductive and convective heat transfer.

The influence of thermal expansion on the ignition delay time.

The flame structure and characteristics in the gas suspensions and gases are essentially different, though their densities are comparable values. The difference is determined by the competitive mechanisms of heat transfer during the process of exothermic conversion. The primary investigation of the gas suspension combustion and ignition was based on the supposition on the existence of one of the dominant stages of heat transfer (conductive, radiative or convective). It is evident that was a conventional approach, since the leading stage could hardly be isolated in the majority of the combustion regimes.

In some earlier study the gas suspension ignition with a heated surface was investigated in the neglection of radiative heat transfer and dynamics of gas fluidity [1]. The dependences of the time required for a gas suspension to be ignited on the basic variables of the problem were determined in the study of the processes of ignition with the aid of the wave theory proposed for the analysis of ignition of homogeneous condensed systems [2]. The present paper reports the further study of initiation of nonstationary process in the gas suspension at the account made of the competitive (conductive and radiative) mechanisms of heat transfer. The influence of thermal expansion on the ignition delay time was also studied during the experiments on the gas suspension ignition in a closed volume.

The Max number M is the parameter characterizing the gas and particle motion. The model proposed implies the suspension rate to much less than the sound speed, $M << 1$. The gas pressure is uniform in space and dependent on time only, $P = P(\tau)$ (homobaric approximation). The combustion modes are considered for the case of the ultimate particle expansion, i.e. at the same gas and particle speed. It is supposed that the particle volume V is constant during of exothermic conversion. The process of combustion is sustained by the reaction on the particle surface (heterogeneous combustion). It is assumed that the exothermic reaction is a one-stage irreversible process. The concentration of a gaseous oxidant contained in excess in the mixture is c_∞ . The thermophysical properties of the combustion products and the green mixture are believed to be the same and independent on exothermic conversion of the condensed phase. It was assumed that the optical properties of the particles and the gas do not change during the reaction. At the diffusion mode of conversion, when the particle temperature is much higher than the temperature of the gaseous environment, a substantial gas flow from the reaction zone may heat up a cold suspension in the pre-flame zone. The radiative heat transfer is described by diffusion approximation. The present model does not take into account the processes of the particle collision and disintegration. The greater attention is paid to the influence of thermal expansion and radiative heat transfer on the non-steady-state processes of the combustion wave initiation and propagation in the closed volume.

Calculation of the ignition characteristics proposed in [2] was based on the fact that the reaction zone with quasistationary distribution of temperature was formed as an intermediate combustion wave (ICW). The process of ignition was divided into three stages:

inert heating with negligibly low heat release, τ_{in} ;

intensification of chemical heat release without noticeable increase in the gas maximum temperature; the stage is accomplished when the gas temperature at the boundary becomes equal to that of the heated surface at τ_0;

disturbance of the heat balance in the reaction zone, τ_{fl}.

The processes of ignition with a heated surface were studied in the supposition that the ignition temperature θ_{in} was lower than the equilibrium temperature of the gas phase θ_∞. At the kinetic regime of the particle conversion, the temperature of the gas phase and a one-temperature ignition mode is observed. Since at the diffusion of the particle conversion in ICW, the temperature of the condensed phase reacting in the combustion zone is much higher than the gas temperature, the process of ignition is of a two-temperature character. The critical conditions of the gas suspension initiation and the ignition delay time depend on the thermal parameters of the reaction zone formation capable of sustaining combustion with no external heat sources applied. The ratio of the specific times of the particle-gas heat exchange to the condensed phase conversion is determined by the parameter z (Semenov criterion).

Consider the process of the gas suspension ignition at the account of thermal expansion. The radiative heat transfer during ignition is disregarded. In the heating zone, the gas density and the particle concentration are decreased because of thermal expansion. During the process of ignition, the maximum value of the mixture velocity is attained at the initial moment of heating. The establishment of the zero gradient of the gas temperatures at the boundary is followed by a sharp increase in a both rate of the heterogeneous reaction and the mixture velocity. Continuous expansion of the heating zone in the course of ignition results in the decrease in the gas density and the particle concentration. The numeric calculation showed the duration of all three stages to be an order of magnitude higher at the account of the dynamics of gas fluidity. The changes in the time characteristics of ignition are determined by the decrease in the gas density in the heating zone and, consequently, in the rate of the heterogeneous reaction. Besides, variation in the gas and particle densites in the heating zone is entailed by the changes in the rate of the interphase heat exchange. The transition from the one-temperature kinetic regime of ignition to the high-temperature diffusion mode of combustion takes place at lower values of z than in the immovable mixture. Figure 1 a a shows the dependence of the delay time of the gas suspension ignition τ_0 on the parameter $z = z(1/r)$, where r is the particle radius. The dependences are plotted either with no account made of the dynamics of the gas fluidity (curve 1) or at the account of the thermal expansion (curve 2). In the immovable mixture, the transition occurs at $z < 1.3$. Thermal expansion of the mixture results in the widening of the transition region. At high values of z ($z > 1.3$) the one-temperature regime of ignition is observed and the ignition delay time is tending to some constant value characteristics of ignition of heterogeneous systems. At $z \to 0$ (enlarging of the particle size), the growth of the τ_0 value explained by the increase in the time of the particle heating up to the ignition temperature. Due to the mixture thermal expansion the transition to the diffusion regime of the particle conversion at the stage of ignition occurs at much lower z values than in the immovable mixture. At the thermal expansion the minimum τ_0 is shifted to the region of lower values of z. The transition from kinetic to diffusion regime was accompanied with jump-wise diminishing of the ignition delay time and the energy required for the combustion process initiation.

Evaluation of the stages of ignition of the gas suspension in the immovable mixture were considered with the aid of analytical approximation [1]. The numeric analysis showed that the nonstationary combustion proceeded in the discharged madium due to the particle motion during the process of ignition. Assuming that during ignition the region of combustion and heating up is much less than the initial volume and $P(\tau) = P_0 = const$, one can easily find the minimum values of the particle and gas densities in the reaction zone. The analytical expressions for evaluation of the ignition stages in the discharge medium in the immovable mixture can be obtained by making use of the approach proposed in [1]. The numeric calculations showed that the as-obtained expressions describe qualitatively the ignition delay time in the limiting cases. At the analysis of the ignition processes in the close-to-transition regions it should be kept in mind that the suspension flux may cause the shift of the two-temperature regime of ignition to the region of low values of the parameter z. In the region of the parameter z corresponding to the diffusion regime of immovable suspension conversion, thermal expansion can lead to the occurrence of the one-temperature regime.

The heat released during exothermic conversion at the moment τ_0 is one of the characteristics of ignition. It was found that the integral quantity of heat at τ_0 was more than in the immovable mixture despite the low particle concentration in the combustion zone resulting from thermal expansion.

Thus, it is obvious that convective motion of the mixture exerts a significant effect on the ignition characteristics. As it could be expected, the analytical formulas obtained for evaluation of the ignition delay time hold well in the limiting cases. Application of approximate expressions to the transition regions requires some additional analysis.

The Influence of radiative heat transfer on ignition of a gas suspension.

High temperature of the condensed component in the conversion zone initiates a radiative flux the reaction zone, which is then consumed by the initial suspension. The width of the zone of radiative heating is of an order of the length of the free run of the front

$$\breve{l} \sim r(\rho_p / \rho)(B^{-1} - 1) \sim (ns)^{-1}$$, where ρ_p is the density of the condensed phase, ρ - is the gas density, $B = mn / (mn + \rho)$ - is the mass portion of the condensed phase, n is the number of the particles per unit volume, $m-$ is the mass of the particle, s is the square of the particle surface. At the increase in the particle size, the free run lengthens and, consequently, primary heating up of the cold particles with the radiative flux is enhanced in the preflame zone. At the kinetic one-temperature regime of combustion during ignition the particle temperature is low and close to that of the heated surface. Fine particles burn quickly, the reaction zone remains optically thin, and the heating of the suspension in the absorption zone is insignificant. At lower parameter z (the particle radius r growth) the transition from the kinetic to conversion regime to a diffusion one is accompanied by the growth of the particle temperature, which becomes higher than that of the a gas, and the increase in the density of the radiative flux in the heating zone and the length of the radiation free run. The growth of the maximum temperature of the particles in the combustion zone promotes the influence of the radiation heat transfer on the processes of ignition. On the other hand, at the increase in the particle temperature during ignition, the heat exchange between the particles and the gas is accelerated and the conductive heat transfer is intensified.

The process of ignition of the gas suspension were studied in the absence of its thermal expansion. The following assumptions were accepted: $z = 1$, the particles radius $r = 30 \mu m$, the Stefan-Boltzmann constant $\sigma = 5.67 \cdot 10^{-8} W / m^2 K^4$, the gas heat diffusivity $a = 0.2 sm / s$, $c = 30 J / mol\ K^0$, $\rho_0 = 1 Kg / m^3$,

ρ^0 is the initial gas density. The decrease in the z parameter (the particles size growth) causes widening of the heating zone. The dependence of the time of the zero gradient establishment τ_0 on parameter z is shown in Figure 1b. At $z > 1.4$, the one-temperature regimes of ignition are observed, the $0.75 < z < 1.4$ range corresponds to the transition regime of the mixture combustion during ignition, at $z \to 0$, combustion proceeds in the two-temperature diffusion regime. In the absence of thermal expansion, the existence of two competitive mechanisms of heat transfer results in the formation of a parametric region, within which the growth of the maximum particle temperature is accompanied by the increase in τ_0 and the particle temperature as compared to the gas temperature.

Enhancement of the radiation flow from the combustion zone initiates radiative heating of the particles in the wide pre-flame zone. The contribution of the radiative heat transfer becomes predominant and the ignition delay time τ_0 increases. The further decrease in the z value (the particle growth) the difference between the particle and gas temperatures becomes more pronounced. The increasing effect of the conductive heat transfer results in diminishing of τ_0. At $z \approx 0.75$ the ignition delay time approaches its minimum, while the difference in the particle-gas temperature in the combustion zone

mounts up to its maximum value. At still further lowering down of the z parameter, an abrupt decrease in the ignition delay time is determined by two factors: the increase in the duration of the particle-gas heat exchange and intensification of the radiative heat transfer in the wide pre-flame zone.

Thus, the radiative heat transfer causes the increase in the time of the establishment of the zero gradient of the gas temperature on the boundary. In the region of the combustion mode transition there appears an additional extremum arising because of the competitive mechanisms of heat exchange.

During gas suspension ignition accompanied by thermal expansion in the heating zone, the gas density and the particle concentration are decreased. The radiative and conductive heat transfer proceeds via the competitive mechanism at even small particle sizes. The τ_0 value is seen to grow at

ignition of a finely dispersed gas suspension ((Fig. $1b$, curve 2). At the increase in the particle radius, the one-temperature conversion regime is rearranged to a two-temperature one and, consequently, the process, the width of the discharged region becomes large along with the length of radiation free run. The heat of the narrow zone of exothermic conversion by the radiative flow is transferred to the wide discharge pre-flame zone. A sharp increase in the ignition delay time that follows leads to the transition from the conductive to radiative combustion mode. As shown previously [3], the velocity of the radiative combustion wave and front width are 2-3 orders higher than at conductive mode. Thus, a wide combustion zone corresponding to the radiative wave structure should be formed for the gas suspension to be ignited. At the particle diameter of $0.01\,sm$ and the mass portion of the condensed phase

$B = 0.3$, the absorption zone in the dust\gas mixture spreads as far $(ns)^{-1} \sim 1\,m$. Therefore, when ignition is considered in the actual closed volume, the radiative heat transfer initiates combustion in the regime of a thermal explosion.
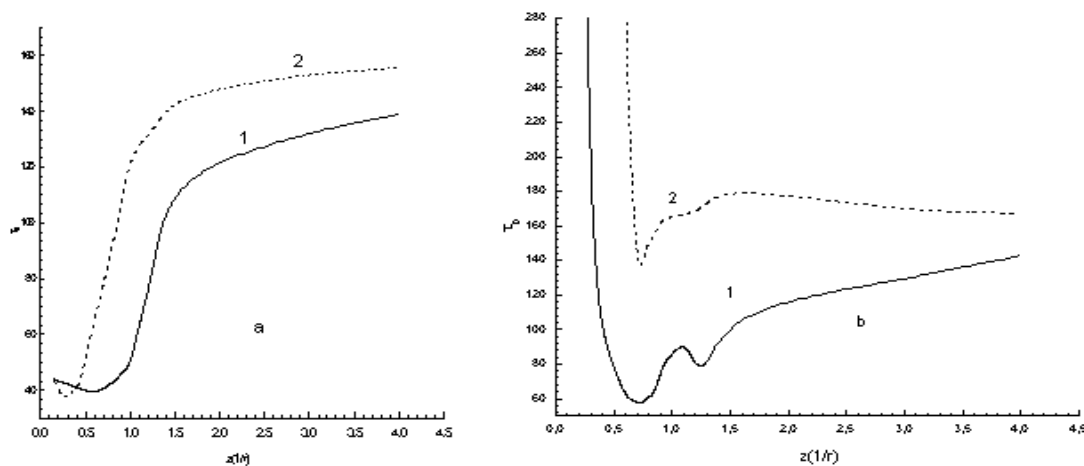
Fig 1. Dependence of the delay time of the dust/gas ignition τ_0 on the parameter z. Dust/gas mixture with parameters:

$$B = 0.3, \beta = 0.06, \gamma = 0.0154, \theta_0 = -11.11, \theta_{in} = 0, \theta_\infty = 8.33, \rho_p / \rho^0 = 10^{-3}.$$

References.

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